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Laser Ablation Mechanism Of Silicon Nitride Layers In A Nanosecond UV Regime

G. Poulain[a,d]*, D. Blanc[a], A. Focsa[a], M. De Vita[a], B. Semmache[b], M. Gauthier[c], Y. Pellegrin[b], M. Lemiti[a]

[a]*Université de Lyon; Institut des Nanotechnologies de Lyon INL-UMR5270, CNRS, INSA de Lyon, Villeurbanne, F-69621, France*
[b]*SEMCO Eng., 625, rue de la Croix Verte - Parc Euromédecine, 34196 Montpellier Cedex 5 – France*
[c]*PHOTOWATT International S.A.S., 33 Rue Saint Honoré, 38300 Bourgoin-Jallieu – France*
[d]*Agence de l'environnement et de la Maîtrise de l'Energie, 20, avenue du Grésillé – BP 90406 49004 Angers Cedex 01 France*

Abstract

Selective laser ablation of silicon nitride (SiN_x) layers is a crucial technological step to achieve alternative front side metallization like electrochemical contact. In this work, we discuss the mechanism of laser ablation with a nanosecond UV laser source. A model with two thresholds corresponding to the melting threshold of silicon and the ablation threshold of silicon nitride is proposed. A finite element method is used to solve the heat transfer equation and describe the ablated SiN_x surface for a single laser pulse. Numerical results are compared to optical microscopy measurements of the ablated zone.

Keywords: laser; ablation; silicon nitride; silicon solar cell; finite element

1. Introduction

Laser processes are becoming more present in the photovoltaic industry because of the many opportunities they offer. Selective laser ablation is a promising way to realise at low cost the structuring of silicon nitride needed to perform electrochemical metallisation on the front side of silicon solar cells [1,2]. In this context, understanding the mechanisms involved in the laser ablation process is crucial.

* Corresponding author. Tel.: +33-04-72-43-87-38
E-mail address: gilles.poulain@insa-lyon.fr

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Previous studies have investigated these mechanisms in the case of picosecond or femtosecond laser at various wavelengths [3,4] and in the particular case of a nanosecond UV laser source [1,5]. UV light is well suited for selective ablation of dielectrics on silicon substrates due to the large absorption coefficients of silicon that ensures a high energy deposition in a small volume. In addition, nanosecond laser sources (in the range of 10 ns) allow to obtain very satisfactory results because of the limited thermal conduction to the surrounding material. In this paper we use microscopic observations and numerical simulation to propose a simple model to explain laser ablation in this regime and quickly evaluate the size of the ablated area.

2. Microscopy studies

Silicon nitride (SiN_x) layers are deposited by PECVD on monocrystalline silicon substrate with polished surface. The properties of the layers are chosen to achieve a standard antireflection coating with a thickness of 75 nm and a refractive index around 2.01 at 635 nm. The laser used for ablation is a frequency tripled Nd:YAG laser with Gaussian profile, a wavelength of 355 nm and a pulse duration of 10 ns.

In order to investigate the ablation mechanism of SiN_x, single spots with a fluence ranging from 0.1 to 1.4 $J.cm^{-2}$ were studied. Observations by optical microscopy show two behaviours. At low fluence, below 0.4 $J.cm^{-2}$, although SiN_x is not ablated, an area with a different optical contrast is observed as the surface under the silicon nitride is thermally affected. At higher fluence SiN_x starts to be ablated and the silicon surface is visible (Fig. 1). Beyond 0.8 $J.cm^{-2}$ the thermally damaged zone is no longer discernible from the ablated zone. For fluences above 1 $J.cm^{-2}$, the ablated areas have elliptical shapes that may be due to a defect of the polarization or some distortion of the laser source. In these cases the diameters are taken as an average between the long and the short axis. Figure 2 shows the variation of the measured diameter of the SiN_x ablated zone and of the thermally affected zone with the laser fluence. From Figure 2, the ablation threshold was estimated to be around 0.4 $J.cm^{-2}$ and the threshold for thermal damage in silicon around 0.2 $J.cm^{-2}$.

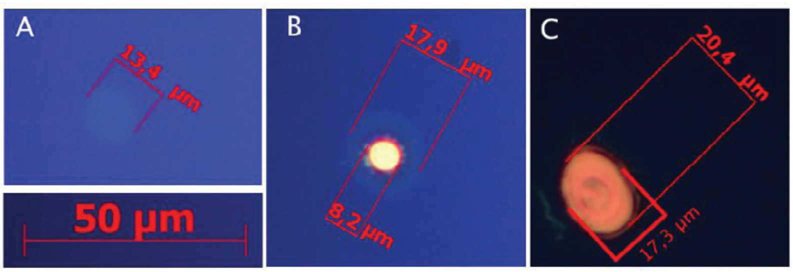

Fig. 1. Optical microscopy image of a laser-ablated spot for a fluence of 0.25 $J.cm^{-2}$ (a), 0.45 $J.cm^{-2}$ (b) and 1.4 $J.cm^{-2}$ (c). Thermally affected zone is also visible on pictures a and b. Same scale

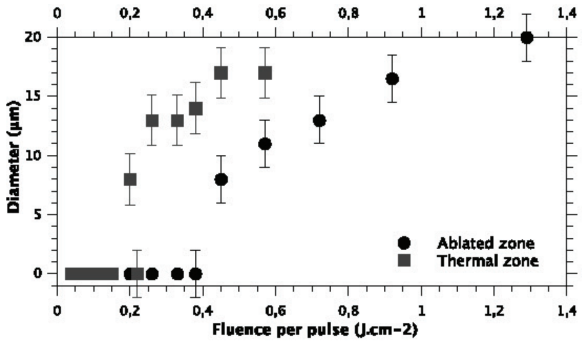

Fig. 2. Measured diameter of the SiNx ablated zone and the thermally affected zone with the fluence

These observations suggest that the ablation process is taking place in two steps. First, the incident laser beam heats the silicon surface, and then heat is transmitted by conduction to the SiN_x layer. For low laser fluences (approximately between 0.2 and 0.4 $J.cm^{-2}$), the temperature reached (around 1687 K) is sufficient to melt the silicon but not to ablate the SiN_x layer. Melting of the silicon surface causes a deterioration of the Si/SiN_x interface due to the thermal expansion of the silicon in its liquid phase, corresponding to the observed thermally affected zone. For higher fluences (above 0.4 $J.cm^{-2}$) the temperature reached at the interface Si/SiN_x is sufficient to locally ablate the antireflections coating.

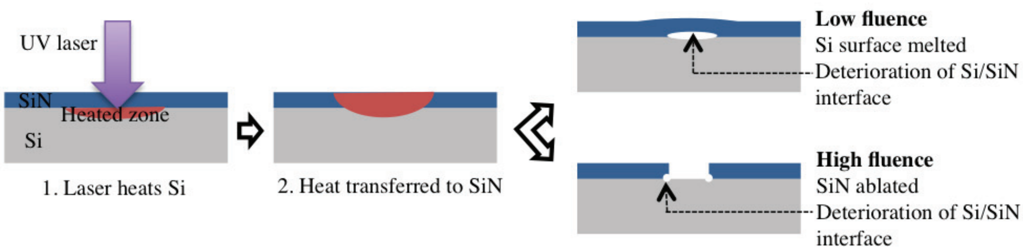

Fig. 3. Proposed mechanism of SiN ablation in UV nanosecond regime

3. Determination of threshold fluences

To evaluate more precisely the laser energies involved during the SiN_x ablation, we assume to have a perfect Gaussian beam (Fig. 4), with a spatial fluence distribution given by

$$F(r) = F_0 \exp\left(-\left(\frac{r}{r_0}\right)^2\right) \quad (1)$$

where r is the distance to the pulse maximum, r0 is the 1/e radius in the focal plane and F0 the pulse maximum. We can consider that the two behaviours observed are threshold phenomena. We express the link between the measured diameter D and the fluence F0 using Eq. (1) :

$$D = 2r_0\sqrt{\ln \frac{F_0}{F_{th}}} \quad (2)$$

In Figure 4, a fit of the experimental data with Eq. (2) is used to determine with more accuracy the threshold fluence Fth of the thermal damage (0.18 J.cm-2) and of the SiNx ablation (0.4 J.cm-2).

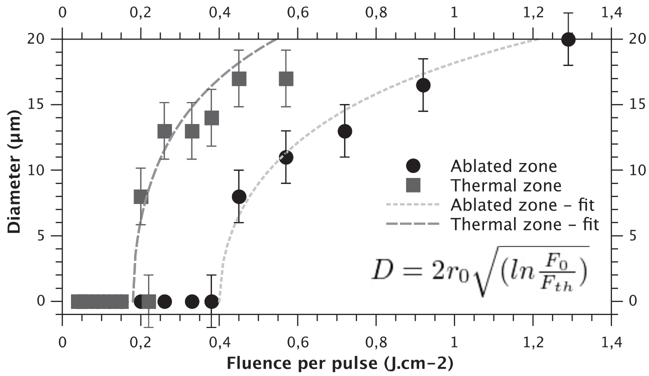

Fig. 4. Fit of the measured diameters of the SiNx ablated zone and of the thermally affected zone as a function of laser fluence

The good quality of these adjustments is consistent with the previously proposed ablation mechanism. Moreover, the diameter of the thermally affected zone and of the ablated zone can be directly estimated using Eq. (1) by the area where the incident laser fluence exceeds the thresholds for melting of silicon or ablation of SiN_x respectively. Indeed if we compare Figure 1b and Figure 5, the experimental and calculated diameter of the thermally affected zone (18 µm) and of the ablated zone (8 µm) agree to within 10%. Thus, Eq (2) can provide a quick estimation of the size of the ablated area for a given fluence.

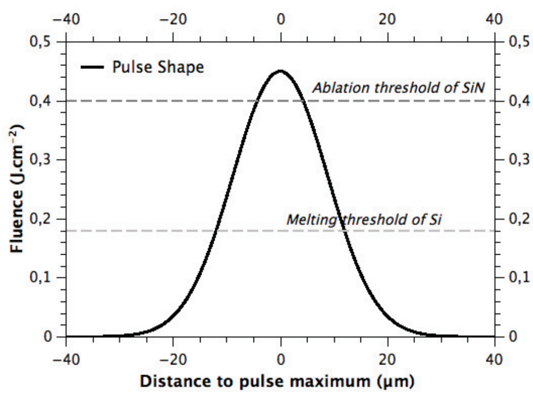

Fig. 5. Pulse shape at 0.45 J.cm-2. Measured thresholds are reported on the graph

4. Finite element simulation

We developed a finite element simulation with COMSOL Multiphysics® [6] to show the thermal behaviour of a SiN_x/Si structure after a single laser pulse. Due to the symmetry of revolution linked to the Gaussian shape of the pulse we solve the following two-dimensional heat transfer equation:

$$\rho(T)C_p(T)\frac{T}{t} = \nabla\left[k_{th}(T)\nabla T\right] + Q \quad (3)$$

$\rho(T)$ is the material density, $C_p(T)$ the specific heat capacity, T the temperature, t the time, k_{th} the thermal conductivity, Q the heat source in volume due to the absorbed laser power. The heat source term Q in the heat-transfer equation corresponds to the absorbed laser power and can be written as follow:

$$Q = \left(1 - R(T)\right)\alpha(T)P_{in}(x,t)I(y) \quad (4)$$

$\alpha(T)$ is the material absorption coefficient, $R(T)$ the surface reflectivity, $P_{in}(x,t)$ the incident laser power and $I(y)$ the relative intensity given by the Beer-Lambert law. The beam is considered with a Gaussian shape in time and space.

, The laser absorption in SiN_x is negligible and therefore the heat source term in this material is five orders of magnitude lower than in Si. The heat absorbed in Si is transferred by conduction in a few nanoseconds to SiN_x. The Si substrate behaves therefore as a heat source after having absorbed the laser energy. We calculated that an incident fluence of 0.18 $J.cm^{-2}$ leads to a temperature around 1687 K in Si, corresponding to the melting of the substrate. A fluence of 0.4 $J.cm^{-2}$ leads to a temperature above 2150 K at the SiN_x/Si interface. Complete removal of SiN_x occurs at this temperature. At this point the partial pressure of N_2 in SiN_x reaches one atmosphere and this leads to the dielectric decomposition [5]. On Fig.5 we observe a reasonable agreement between experimental data and simulated diameters of the area where the calculated temperature at the interface of the two materials is above 1687 K and 2150 K. However, for fluence above 0.6 $J.cm^{-2}$ discrepancies between experimental and calculated data are observable. This may be explained by the fact that our model is a first approximation as the partial removal of SiN_x over time is not taken into account. Indeed for high fluences, simulation results show areas in SiN_x where the temperature greatly exceeds 2150 K. Future improvement of our simulation tool will allow us to consider these area as ablated and to take into account the changes in the thermal properties of the structure induced by bare silicon. Furthermore the screening of the laser beam by the plasma plume that results from the ablation mechanism may explain the reduced experimental diameters compared to the theoretical ones.

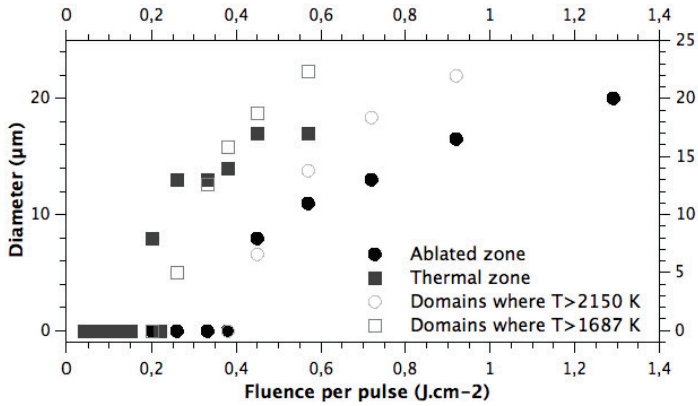

Fig. 5. Experimental (●, ■) and simulated (○, □) diameters of laser-matter interaction

Finite element simulation seems to confirm the mechanism proposed from optical observations. Above the first threshold (0.18 $J.cm^{-2}$) the silicon substrate is melted causing the deterioration of the SiN_x/Si interface. Above the second threshold (0.4 $J.cm^{-2}$) the temperature at the interface SiN_x/Si exceeds the value corresponding to the dielectric decomposition (Fig. 1 and 4).

5. Conclusion

Laser ablation mechanism of SiN_x on silicon was studied with a nanosecond UV laser. Due to the relative low absorption coefficient of the SiN_x in the UV, most of the incident laser energy is absorbed by the silicon substrate. Consequently the silicon is heated and the heat is transmitted by conduction to the upper layer. Two threshold phenomena are observed starting from the deterioration of the Si/SiN_x interface due to the melting of silicon at low fluence followed by the decomposition of the SiN_x layer at fluence higher than 0.4 $J.cm^{-2}$. These assumptions made on the ablation mechanisms are confirmed by numerical simulation using finite elements. Finally, the calculation of the area where the incident laser energy exceeds the ablation threshold is a good approximation of the measured size of the ablated zone.

Acknowledgements

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References

[1] A. Knorz, M. Peters, A. Grohe, C. Harmel, R. Preu, Selective laser ablation of SiNx layers on textured surfaces for low temperature front side metallization, Prog. Photovolt: Res. Appl. 17 (2009) 127-136.

[2] A. Knorz, M. Aleman, A. Grohe, R. Preu, S.W. Glunz, Laser Ablation of Antireflection Coatings for Plated Contacts Yielding Solar Cell Efficiencies Above 20 %, in: 24th European PV Solar Energy Conference and Exhibition, Hamburg, 2009.

[3] G. Heinrich, M. Bähr, K. Stolberg, T. Wütherich, M. Leonhardt, A. Lawerenz, Investigation of ablation mechanisms for selective laser ablation of silicon nitride layers, Energy Procedia. 8 (2011) 592-597.

[4] V. Rana, Z. Zhang, C. Lazik, R. Mishra, T. Weidman, C. Eberspacher, Investigations into selective removal of silicon nitride using laser for crystalline silicon solar cells, in: 23rd European Photovoltaic Solar Energy Conference, Valence, 2008.

[5] S.A.G.D. Correia, J. Lossen, M. Wald, K. Neckermann, M. Bähr, Selective laser ablation of dielectric layers, in: 22nd European Photovoltaic Solar Energy Conference, Milan, 2007.

[6] Poulain, G., D. Blanc, B. Semmache, Y. Pellegrin, and M. Lemiti. “Finite Element Simulation Of Laser-Induced Diffusion In Silicon.” Energy Procedia 8 (January 2011): 587-591. doi:10.1016/j.egypro.2011.06.187.